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Research paper

The Influence of Time on the Density and Detonation Velocity of Bulk Emulsion Explosives – a Case Study from Polish Copper Mines

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Abstract: The basic method for emulsion matrix sensitisation is chemical reduction of the density by producing *in situ* gas bubbles. The mixing of the components takes place directly inside the loading hose, which is equipped with a mixing device. Due to the multi-component nature of the mixture, the precise dosing of individual components has a key influence on the detonation behaviour of the final product. Unfortunately, keeping the mixing and charging of UG mobile units in good working condition in underground mines is a considerable challenge. As a result, completely different detonation parameters may be observed when charging the same explosive into blast holes using two different units. The aim of the present study was to determine the behaviour of the mechanically loaded emulsion explosives used in Polish underground copper mines by tracking the changes in the density and detonation velocity over time. Samples of the explosives were collected from selected mobile units. In addition, the influence of the quantity of the sensitising agent on the changes in the emulsion density and VOD was studied.

Keywords: blasting, emulsion explosives, VOD, density measurements, chemical gassing

Nomenclature:
UG Underground
VOD Velocity of detonation [m/s]

1 Introduction

Bulk emulsion explosives have been used in large-scale mining operations across the globe for decades. Many factors influence the efficiency of this process, but it appears that the primary factor is the quality of the loaded explosives. This is particularly true for bulk emulsion explosives, which are manufactured directly at the blasting location. Different types of explosives are currently used at KGHM Polish copper mines, which depend on the desired effect of the blasting work and the rock mass parameters. The average annual consumption of bulk emulsion explosives is about 12-14 thousand tonnes, which is 70% of all explosives used in KGHM's mines.

Water-in-oil emulsion explosives are composed primarily of oxidizers, fuels, water and emulsifiers, as well as sensitising agents. Their detonation parameters depend, among others factors, on the content of individual components and the physicochemical properties. The emulsion matrix has no components that are explosive and therefore it needs to be sensitised. The sensitisation methods are based on matrix density reduction, *i.e.* physical sensitisation using low bulk density substances (*e.g.* microballoons) or chemical sensitization, which uses chemically generated gas bubbles. The former is utilised primarily for packaged explosives, whereas for bulk emulsion explosives, due to technological and safety reasons, these are mostly sensitized by the chemical method. During the chemical gassing, the density of an emulsion matrix is reduced from 1.4-1.5 to 0.9-1.2 g/cm^3. This means that correct gassing of the emulsion is essential for good physical stability of the end product [1]. Due to technological and organizational reasons, the time elapsed between the loading and firing of these explosives in KGHM's mines varies between 30 min and 48 h. The loading of the blast holes is conducted by around 45 mixing-charging units installed on blasting utility vehicles. The mixing of the components takes place directly inside the loading hose, which is equipped with a mixing device. Unfortunately, keeping these 45 mobile charging units in good working conditions is a considerable challenge. As a result, completely different velocities of detonation may be observed when charging the same explosive into blast holes using two different units. This raises doubts that not all of the blast holes are fired at densities that are optimal for a given explosive, which can influence the effects

of blasting fragmentation. The following paper presents results that reveal the influence of time on the density and detonation velocity, based on bulk emulsion explosives utilised in Polish copper mines. Samples of the explosives were collected from randomly selected mixing-charging units.

2 Detonation Characteristics of the Bulk Emulsion Explosives

Since the efficiency of explosives is crucial from the point of view of a mine's production capacity, many analyses, including laboratory analyses, are conducted in order to evaluate their behaviour under different conditions, *e.g.* for temperature or pressure [2]. One of the basic parameters characterising an explosive's properties is the velocity of detonation (VOD), which describes the speed at which the shock wave front propagates through an undetonated explosive. This is a measurable parameter that describes the efficiency of a given explosive. Many factors influence the VOD of bulk emulsion explosives, including [3]: the type of sensitiser [4], the temperature of the explosive and ambient temperature [5], the type and size of the booster [6, 7], the time from loading to firing [8, 9], the critical diameter [10, 11] and the density of the charge [12]. As Türker [13] has noted, the determination of relationships between selected parameters of explosives and their efficiency is essential for formulating reliable and credible computational models describing the detonation process. For hard rocks, the use of explosives with a relatively high VOD is usually associated with a higher blasting efficiency than with those which detonate with relatively low velocities [14]. This results from the relationship describing the detonation pressure (P_d), based on which one may notice that a decrease in both VOD and density leads to a detonation pressure decrease and consequently a reduction in the impulse of the energy generated [15, 16]:

$$P_d = \frac{\rho_{ex} \cdot C_d^2}{\gamma + 1} \tag{1}$$

where: ρ_{ex} – initial explosive density, C_d – velocity of detonation, γ – isentrope exponent of the detonation products.

Based on many research studies [17-19], changes in the density and diameter of the explosive charge influence the efficiency of the explosive and its initiation capacity. Low-density bulk emulsion explosives are characterised by a very high sensitivity to initiation [20]. Such explosives are less powerful than those of higher densities, which in turn are associated with lower sensitivity but higher

velocity of detonation and energy concentration. Thus emulsion explosives are required that ensure a controlled sensitising process and the highest energy concentration in the final product. It is assumed that each bulk emulsion explosive has a specific density value at which the detonation velocity reaches its highest value. With the passage of time and a reduction in density below the specified value, the VOD also decreases only becomes stabilised when the density has stabilised. This relationship is presented in Figure 1. It may, therefore, be stated that the blasting effectiveness decreases with a decrease in the density of the emulsion explosive [19].

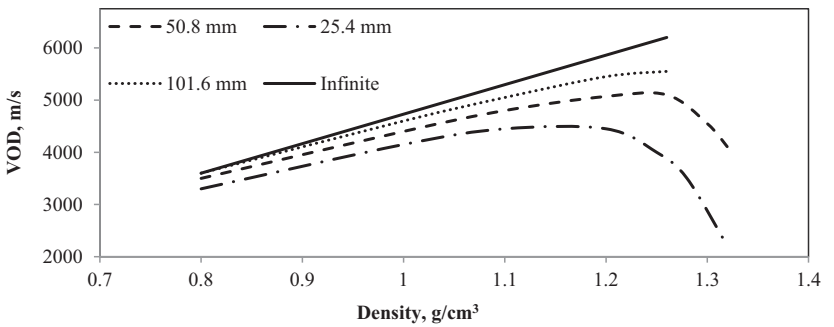


Figure 1. An exemplary dependence of the VOD on the diameter and density [19]

It is obvious that the curve turning point, describing the maximum explosive efficiency, will be different for different types of explosives. This is why it is so important to control the actual densities of bulk emulsion explosives for underground blasting. The key factor that may influence the course of density changes over time is the proportion of sensitiser to the matrix volume, as well as the ambient temperature. This may be controlled by calibration of the mixing and loading mobile units, so that the proportion is appropriate and the end product achieves the required VOD.

3 Experimental

3.1 Density measurements over time

The research consisted of density measurements of bulk emulsion explosives over time. The explosive samples were collected from four, randomly selected, mixing-charging UG mobile units, 10 samples from each unit. Two types

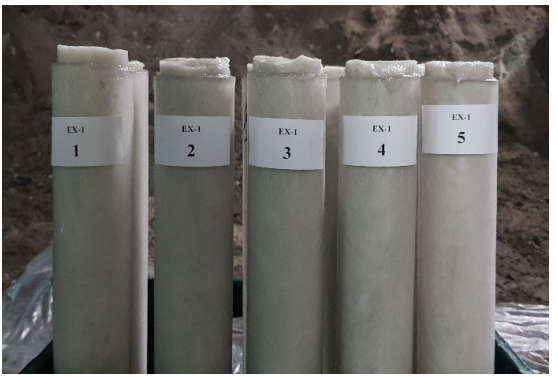
of bulk explosives currently used in Polish copper mines were considered: Emulinit 8L (20 samples), manufactured by NITROERG, and Emulgit RP-T2 (20 samples), manufactured by MAXAM. Both emulsions need only one additive to initiate the gassing reaction. The selected parameters of the tested explosives are listed in Table 1.

Table 1. Selected parameters of the tested explosives (based on technical data sheets)

Parameter	Emulinit 8L	Emulgit RP-T2
Density [g/cm^3]	0.8-1.25	1.05-1.15
Critical diameter [mm]	34	30
Velocity of detonation [m/s]	3800	3200
Heat of reaction [kJ/kg]	3084	3392
Trauzl lead block test [cm^3]	225	236

The tests were based on mass measurements of explosive samples at selected time intervals after loading. They were carried out in a single shift. The samples were prepared by filling clear plastic pipes, internal diameter 50 mm and length 500 mm, with the explosive. This enabled a visual assessment of the mixing correctness of the emulsion matrix with the sensitiser and ensured that there were no voids in the samples. Each pipe was measured (mass and volume) prior to loading. This was done to increase the precision of the density determination. The weight of explosive in each sample was 1.4 kg. The explosives were collected directly from the end of the hose of the mixing-charging UG mobile units that were loading the blast holes. The aim was to make the explosive as homogeneous as possible. Figure 2 shows samples from a selected test after loading and during the gassing process.

(a)



(b)

Figure 2. View of the samples after loading (a), and during density determination (b)

The sample mass measurements were performed using an electronic balance with an accuracy of 0.1 g. During the gassing process the excess of explosive was removed by scraping it from the top and the sample was reweighed. Each subsequent measurement was conducted in the same way. The density was determined by dividing the weight of the sample (without pipe) by the volume of the pipe. The results for 3 of the mixing-charging UG mobile units considered are shown in Figure 3.

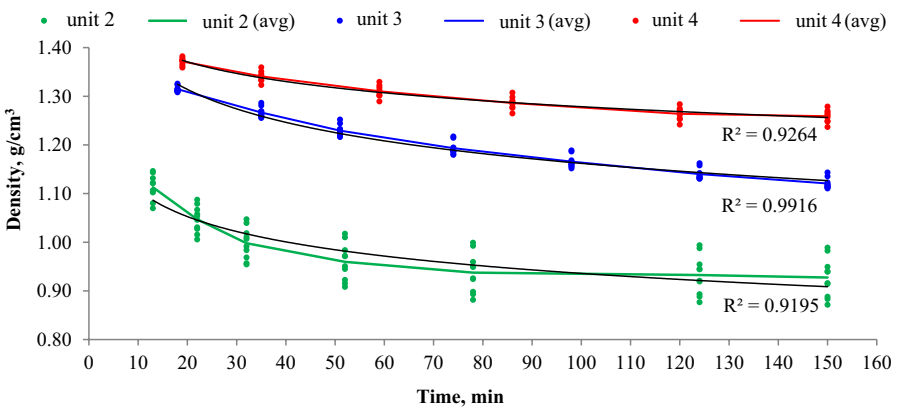


Figure 3. Graph of density of the tested explosives over time for three different units

The measurements proved that the initial values of the explosive densities were different for the samples collected from each unit. They can differ

by as much as approximately 0.25 g/cm^3. Furthermore, in each case the decrease in density occurred at a different rate. The stabilisation of the density, which means that no further density decrease occurred in the following tests (*i.e.* the gassing reaction had finished) also took different lengths of time. The quickest stabilisation occurred for unit no. 2, in which the density remained unchanged after approximately 80 min after loading. However, the greatest dispersion of results was also observed for this unit, and in some cases this amounted to nearly 0.1 g/cm^3. Unfortunately, no changes in the density over time were observed in any of the samples loaded from unit no. 1 and therefore determination of the density was not possible. This could suggest an incorrect sensitisation process.

3.2 Changes of density *vs.* percentage of sensitiser

Based on the results obtained, the authors decided to conduct further research on the influence of the percentage of the sensitiser solution on changes to the explosive density over time. The aim of this study was to verify the character of the gassing reaction and its dependence on the amount of sensitiser added, which may be varied by adjusting the rotational speed of the screw pump in the mixing and charging unit. The flow rate of the pump is regulated based on the periodic calibration of the unit. The objective of the calibration is to check whether the desired volume of the sensitiser solution is dispensed at a given pump rotation. A mixing-charging UG mobile unit in which the rotational speed of the pump could be set manually on the controller was selected for the tests. Three different speeds of pump rotation were considered, *i.e.* 120, 170 and 220 rpm, where 170 rpm for this particular unit was determined to be an optimal speed. The same pipes with the same dimensions, as in the previous tests, were used. To obtain the averaged results, each series corresponding to a given pump rotation speed, consisted of 10 explosive samples. All of them were filled with the same, single type of explosive described in Table 1. As before, each pipe was measured and filled with 1.4 kg of the gas sensitized emulsion explosive. The loading of each series was preceded by pumping out and disposing of approximately 15 kg of the explosive emulsion mixture, in order to obtain a homogeneous explosive sample. The results are presented in Figure 4. The tests were carried out for 120 min for each pump rotation speed. The frequency of the measurements depended on the rate of volume increase of the explosive. The greatest frequency was applied for the samples loaded at the speed of 220 rpm. Once the rate of increase in volume began to slow down, the measuring frequency was reduced.

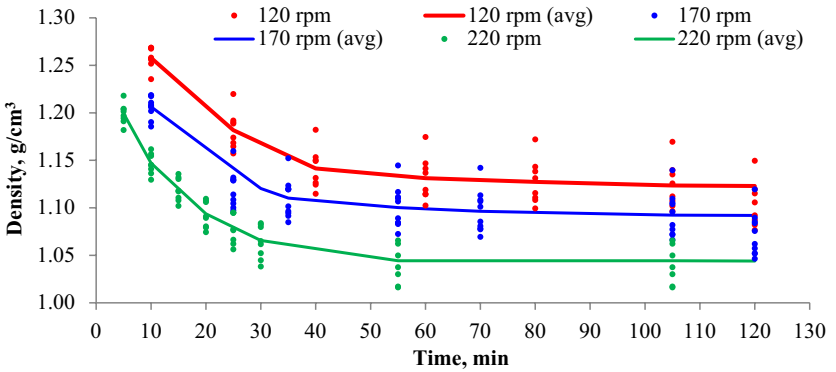


Figure 4. Graph of density changes over time for different pump speeds

As expected, the highest initial density was observed for the lowest pump speed, and the lowest initial density for the highest speed. It can therefore be stated that the more sensitiser there is in a mixture, the faster the gassing process occurs. The trends of the densities *versus* time on the graph are very similar, which proves the correctness of the gassing reaction for each series and the stability of the tested explosives.

3.3 Detonation velocity changes over time

For the purposes of analysis, additional samples for VOD measurements were prepared at the same time as the explosive charges for density measurements, in order to determine the correlation between the detonation velocity of the bulk explosive and its density. This involved 30 samples, 10 for each pump speed. The explosive samples were prepared by filling polypropylene sewage pipes, of internal diameter 46 mm and length 100 cm, with the explosive. This is the typical diameter of the blast holes used in underground Polish copper mines. Each pipe was filled with approximately 2.8 kg of explosive. This amount guaranteed that they would be fully filled after gassing. Samples were equipped with MREL's VOD Probe Rods with a unit resistance of 331.7 Ω/m and fired using an instantaneous electrical detonator. Measurements were conducted using a MicroTrap VOD/Data Recorder enabling the continuous measurement of the detonation velocity of the explosives.

When measuring VOD, the recorder is triggered by the signal received from the probe placed inside the explosive sample. During detonation the length of the probe is reduced, which also reduces the resistance of the circuit. As a result, the device registers a decrease in voltage as a function of time, and then converts the recorded data into a graph of distance *versus* time,

i.e. the velocity of detonation. The uncertainty of this type of measurement is mainly associated with the variability in unit resistance of the probes and results in a ±2% error in VOD. The measurements were conducted in selected mining drifts of the Polkowice-Sieroszowice mine. The samples were placed on the floor of the drifts and the recorder was located at a secure distance, approximately 100 m away from the firing area. Charges were fired at intervals of 15 min. The detonation of each sample was preceded by a density measurement. The results are presented in Figures 5 (120 rpm), 6 (170 rpm) and 7 (220 rpm).

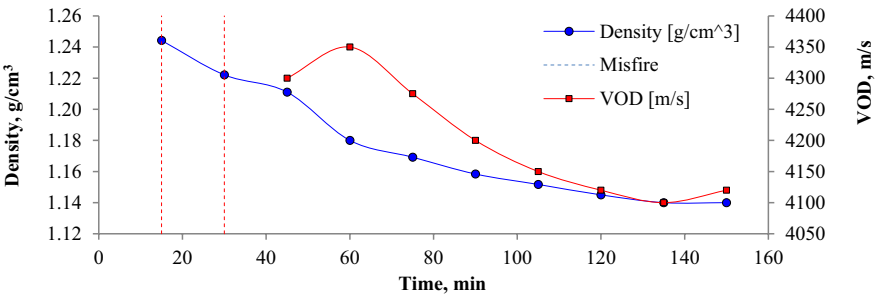


Figure 5. Graph of density and VOD over time at 120 rpm pump rotation speed

A relatively high initial density was observed at a pump speed of 120 rpm. The densities of the first two charges were 1.24 and 1.22 g/cm^3, respectively. These charges did not detonate, which most likely resulted from their density being too high, low sensitivity levels and the relatively small initiation energy. However, the remaining 8 charges did detonate. The recorded VOD demonstrated a trend analogous to the explosive density changes. The VODs and densities within this series became stabilised approximately 120 min after loading and were approximately 4100 m/s and 1.14 g/cm^3, respectively.

Increasing the pump rotation speed to 170 rpm was accompanied by a decrease in initial density, which was equal to 1.15 g/cm^3 after 15 min, and gave a detonation velocity of 4200 m/s. However, the peak VOD value of 4295 m/s was observed 30 min after loading at a density of 1.13 g/cm^3. A decrease in both VOD and density was observed for the other charges. The stabilisation of these parameters was observed approximately 90 min after loading (density 1.07 g/cm^3, VOD 4100 m/s).

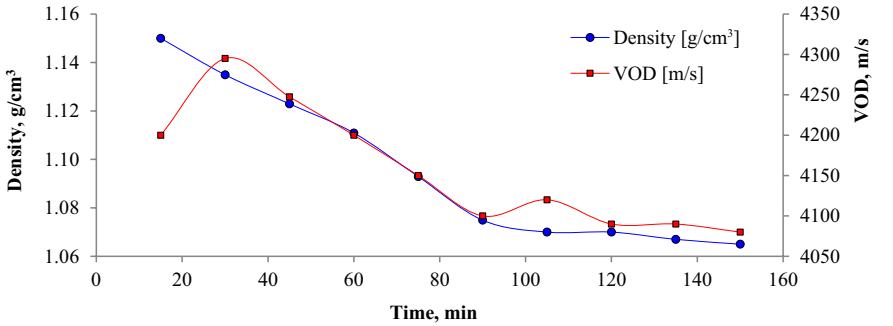


Figure 6. Graph of density and VOD over time at 170 rpm pump rotation speed

A further increase in pump rotation speed resulted in acceleration of the chemical gassing, which was accompanied by a quicker decrease in explosive density over time. The density of the first sample measured after 15 min was 1.12 g/cm^3, with a VOD of 4100 m/s. In this case, the stabilisation of the detonation velocity and density occurred very quickly, *i.e.* in approximately 70 min. Finally, the emulsion explosive density at this pump speed was 0.95 g/cm^3, and the velocity of detonation was approximately 4040 m/s.

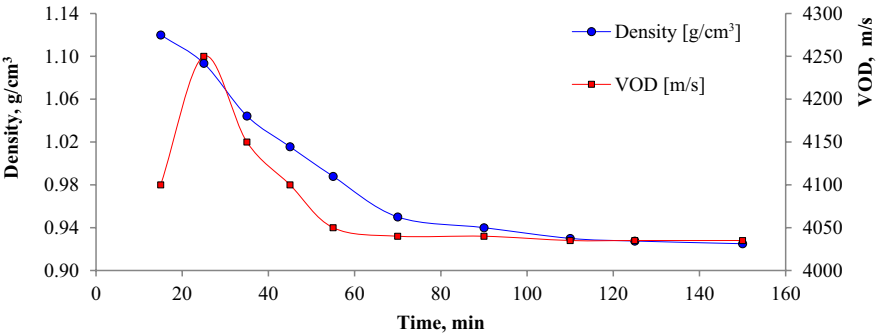


Figure 7. Graph of density and VOD over time at 220 rpm pump rotation speed

4 Results and Discussion

Based on the results of the measurement of the emulsion explosives' densities as a function of time, significant differences were observed between individual mixing and loading units, both in the nature of the changes and the initial values of the density. The initial densities of samples loaded using different units varied by nearly 30%. Moreover, no changes in density over time were observed

for samples collected from one of the examined units. This means that the gassing process was incorrect or not even initiated. A detailed analysis of this case showed that there were no mixing devices inside the loading hose in this mixing and loading unit. Thus, the blending of the components of the explosive compound was impossible. From the point of view of blasting efficiency, the stabilised density of the charges seems to be a key factor. However, significant differences were still observed as: the average densities were 0.92 g/cm^3 for samples loaded from unit no. 2, 1.14 g/cm^3 for samples from unit no. 3 and 1.26 g/cm^3 for samples from unit no. 4. It should also be noted that the same type of explosive was loaded from mixing-charging unit nos. 1 and 2, while the other was from unit nos. 3 and 4. The differences between the results may suggest incorrect dosing of the bulk emulsion explosive components. In such cases, calibration of the mixing-charging UG mobile units is required. According to the procedure used, each loading of blast holes must be preceded by a density measurement of the emulsion, which is conducted by a shot firer. This test consists of charging cups of a known volume and measuring the changes in emulsion explosive density over time. In the case of an incorrect gassing process, the loading unit needs to be recalibrated.

In order to determine the influence of the quantity of the sensitiser solution on the gassing process (density and VOD) additional studies were carried out. The amount of sensitiser solution was varied by adjusting the rotation speed of the screw pump. Spearman's correlation coefficient *()* was calculated for the results obtained at the tested pump speeds, using the following formula:

$$r_s = 1 - \frac{6\sum_{i=1}^{n} D^2}{n(n^2-1)} \tag{2}$$

where: n – number of measurements, D – difference between ranks. The values of Spearman's coefficient were: 0.94 for 120 rpm, 0.98 for 170 rpm and 0.98 for 220 rpm, which can be interpreted as a very strong and almost perfect correlation between density and detonation velocity. A graphical summary of the VOD changes as a function of emulsion explosive density based on Figures 5-7 is presented in Figure 8.

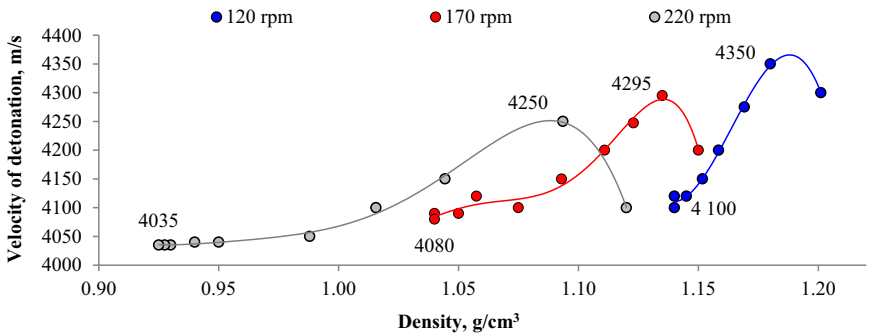


Figure 8. Graph of VOD changes depending on explosive density for the tested pump speeds

The relations obtained between the VOD and the emulsion explosive density are similar to those shown in Figure 1. This confirms the theory that each emulsion explosive has a specific density at which the VOD has the highest value. Thus, compositions of bulk emulsion explosives should be developed, for which the sensitisation process will occur smoothly and the end product will be characterized by the slowest decrease in density over time.

5 Conclusions

The results for the influence of time on the density and detonation velocity of bulk emulsion explosives as parameters for describing the detonation process of an explosive, developed within the framework of this paper, have demonstrated that those parameters are highly variable over time, especially within the first few hours of loading. Considering the fact that explosives under the Polish copper mine conditions can be fired between 30 min and 48 h after loading, it may be concluded that not all blast holes are fired at densities that are optimal for the applied explosives. In order to ensure the maximum efficiency of blasting operations, explosives in mining faces would need to be fired at the shortest possible time after loading. The analysis presented clearly shows that the injected quantity of sensitiser solution has an influence on the speed of the gassing process. This means that less sensitiser in the emulsion matrix results in a higher initial density. In principle, such an explosive is characterised by a relatively high energy concentration and low sensitivity. On the other hand, too high a sensitiser content results in a sharp decrease in density over time, which in turn negatively influences the detonation velocity and the efficiency of the blasting. It should

therefore be considered whether boosters should be used, not only when hard rock is present, but also when the explosive in the blast holes are fired several hours after loading.

The lack of reproducibility of the parameters of the bulk explosives mixed from the same components but using different mixing-charging UG mobile units is an important issue. Designing blasting operations using advanced computer tools may not result in the desired effect due to a lack of reliable parameters describing the behaviour of an explosive. In order to maintain the appropriate efficiency of blasting operations, both unit calibrations and *in situ* measurements of density and VOD of explosives should be performed periodically. It can also be assumed that despite decades of experience in the field of mechanical loading of emulsion explosives in KGHM's mines, a significant number of mining faces may be fired outside the optimal density range. Perhaps a change in the gassing reaction should be considered, which could be achieved by changing the composition of the sensitiser, so that the explosives are better suited to the applied mining system.

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